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MODELING OF THE NON-AUDITORY RESPONSE TO BLAST OVERPRESSURE

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The goal of this project is to develop mathematical models of the physical processes that cause blast injury so that the results of these tests using animals in simple blast environments can be safely translated to estimating hazard to man exposed to blast both in the free field and within enclosures. The present project builds upon an earlier work to develop models of the mechanics of the thorax and lung exposed to simple blast waves. The scope of interest has been expanded to include the lung, the gastro-intestinal tract, the upper respiratory tract, and the tympanic organs and to include a more extensive investigation of the magnitude and distribution of loading under a wider range of blast situations. The report covers the first year of the contract. Effort was concentrated in formulating a specific mathematical approach to each organ system, collecting and analyzing data from previous field tests, and developing models that can provide preliminary Damage Risk Criteria for the most susceptible organ system, the upper respiratory tract.

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Summary

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The present project builds upon an earlier work to develop models of the mechanics of the thorax and lung exposed to simple blast waves. The scope of interest has been expanded to include the lung, the gastro-intestinal tract, the upper respiratory tract, and the tympanic organs and to include a more extensive investigation of the magnitude and distribution of loading under a wider range of blast situations.

This report covers the first year of the contract. Effort was concentrated in formulating a specific mathematical approach to each organ system, collecting and analyzing data from previous field tests, and developing models that can provide preliminary Damage Risk Criteria for the most susceptible organ system, the upper respiratory tract.

Research Area 1: Load Determination

The goal of this area of research is to develop the models necessary to convert environmental parameters into the load distributions used in the body response models.

Blast wave literature reviewed

The literature on the relation of explosion to free field waves and loading at normal incidence was collected, reviewed, and summarized. A variety of tables, charts, and formulae were produced showing the dependence of blast characteristics on the explosive strength, distance, and height of burst. These relations will be used when the environment is known in terms of the explosive charge itself and the distance to the subject.

Prediction of loading from free-field pressure

Based on the information gathered in the literature review, a procedure was developed to relate loading at normal incidence to the properties of the free field pressure signal. The procedure will be used when the environment is defined in terms of a single pressure gauge side-on to the blast.

Comparison with 1985 field data

The relations developed in the first two items were tested against the explosive, free-field, and load data gathered at the Albuquerque test facility. At low pressure levels, the data was highly repeatable shot-to-shot and agreed satisfactorily with the collected formulae, when all geometric corrections were properly made. At high pressures, however, there was more variability in the data and the agreement with prediction becomes less accurate. Generally, the models predict the free-field better than the loading and the peak pressure better than the impulse.

Measurement standard

Where possible, it is preferable to measure the load distribution directly, rather than trying to infer it from the environment. To this end, a device for standardizing the load measurement was conceived by JAYCOR and Walter Reed Army Institute of Research personnel.

The following considerations entered into the design. A circular cross-section of standard 12" diameter was chosen so that the device can be constructed from materials readily available anywhere in the world. Four pressure transducers, flush mounted to the cylinder at the axial midpoint, one in each quadrant, give the circumferential distribution of load. An axial length of 30" was chosen to reduce end effects. The cylinder can be mounted vertically to approximate the geometry of a man or mounted horizontally from end supports to approximate a sheep.

Laboratory experiments were conducted that determined that the pressure transducer response was not affected by the curvature, compliancy, or acceleration of the surface. Pressures encountered in the field are much larger, so the design may have to be modified. The first model was delivered to the Albuquerque test facility for use in the 1986 summer tests.

Research Area 2: Application to Upper Respiratory Tract (URT)

The goal of this research area is to produce a mathematical model that can predict the risk of injury to the URT in a wide variety of blast environments.

Data base of URT injury

Existing data on injury to the URT from free field blast was collected into a single data base. A consistent definition of injury was devised that allowed data from different tests to be combined. Graphical plots were produced of the resulting Damage Risk Criteria for various levels of injury and for various number of repeated exposures.

Simplified model

A simplified model for the structural response of the URT was combined with the formulae describing loading to produce a unified Damage Risk Criteria prediction methodology. The hypothesis of the model is that injury occurs when the maximum stress generated in the structure exceeds a material strength value. Progressively greater injury corresponds to progressively larger critical stresses. The effects of repeated exposure are represented by the reduction of critical stress by fatigue.

The model was calibrated against the URT injury data base described above. Four critical stress values were chosen to represent the four levels of injury observed and a single value was chosen to represent the logarithmic decrement in strength per exposure.

The five model parameters were able to correlate the DRC data for four levels of injury for repeated exposures of 1, 5, 20, and 100. The model can be used to extrapolate the existing data to environments not tested and to other numbers of exposures.

Research Area 3: Application to Lung

The goal of this research area is to provide a mathematical model that can predict the risk of injury to the lung in a wide variety of blast environments.

Analysis of 1985 field data

The verification of earlier structural models of the thorax has been hampered by the lack of direct measurement of the mechanical response of the chest wall and lung during blast exposure. To provide this data, WRAIR conducted instrumented animal tests at the Albuquerque facility during the summer of 1985. That data was reduced by JAYCOR and placed in a data base on JAYCOR's mainframe computer. Graphic packages were written to display each data trace recorded and to overlay combinations of traces.

Multiple shot data was combined and averaged to give response data that could be compared with model prediction. Consistency checks were made that revealed that the chest wall acceleration measurements were incorrect and that some internal pressure measurements were clipped.

In most cases, the intrathoracic pressure response was the same for every shot. In the one case in which injury occurred, however, the interior pressures showed a progressive change with shot that may be the first indication of the mechanical effects of injury.

2D Finite Element Model

The 2D Finite Element Model (FEM) of the thorax, developed under an earlier contract, was converted from the unsupported computer program FEAP to the commercially supported program ADINA. ADINA allows a wider range of material properties, improved numerical algorithms, and better graphical support. The previous calculations were re-run and produced the same results.

The FEM employed a simple rule for transforming the free field pressure history into a distributed loading. This rule was developed from earlier tests that involved long duration blast waves. This rule underpredicted the loading and consequently the ITP response under the 1985 summer test conditions. When it was corrected, based on our findings in Research Area 1, the agreement was as satisfactory as had been demonstrated earlier.

1D Finite Element Model

The principal limitations of the 2D FEM are its treatment of the sharp material property differences between the chest wall and the lung and its limited spatial resolution of the parenchymal wave. To study means of correcting these deficiencies, a 1D FEM was constructed with a special treatment to handle the chest-lung boundary and adequate resolution to follow the wave motion.

The lack of chest wall motion data and clipped pressure traces prevented a quantitative verification of the 1D FEM using the 1985 summer data. Qualitative agreement was achieved and the results were used to formulate a modified test plan for the 1986 field tests.

Analysis of 1986 field data

Based on the experience gained in reducing the previous year's field data, a streamlined data acquisition, transfer, and reduction was devised to support the 1986 Albuquerque tests. Data was recorded on-line to a PC on removable hard disks and shipped to JAYCOR for processing. An automatic translation software package produced graphical output and analysis that was sent back to the field to help guide testing as it proceeded. The data was also added to the existing data base and compared with results from the previous year.

Completion of lung weight experiments at UCSD

Experiments at UCSD, begun under the previous modeling con tract, were completed. Increase in the weight of an isolated, perfused lung was measured in time following an impact to the pleural surface. The results show a distinct threshold for injury when the velocity of the plastic projectile striking the surface reached 13 m/sec. This result is believed to coincide with the formation of parenchyma wave of critical strength in analogy to the formation of a shock wave in a gas.

Small animal protocol

Animal data from the field shows that ITP response increases as the strength of the blast wave increases, however, it does not allow one to determine which aspect of the response (peak pressure, positive impulse, duration, etc.) is responsible for the injury. Therefore in complex wave conditions, even if the lung response model can predict perfectly the local pressure variations, it is not evident how to translate the result into an estimate of injury.

It would be desirable to produce local lung pressures with arbitrary, controllable variations in order to determine which aspect is injurious. This goal is impractical for large animals exposed to charges in the field, but it can be achieved in small animals in the laboratory.

The working hypothesis is that, while the external structure of large and small animals differ greatly and therefore the nature of the external blast environment that produces injury will differ between species, the differences in the biomechanical properties of parenchyma are small and that local stress will correlate with local injury.

A test apparatus has been constructed in which the environment can be controlled over a wide range of over and under pressures.

Injury mechanisms

Two mechanisms for the process by which parenchymal waves cause injury to the lung have been proposed. These hypotheses will be tested and refined based on the small animal protocols described above.

Both models relate injury to an excessive stress in the lung tissue. The first model relates the tissue stress to the differential pressure across the alveoli, in analogy to the relation that governs the surface tension in a balloon. The other model relates the stress to the absolute pressure within the parenchyma, using the equation of state to predict the volume changes. There is some qualitative agreement with data from these models but a final resolution of the mechanism will depend on the analysis of the small animal protocol.

Research Area 4: Application to Gastro-Intestinal Tract

The goal of this research area is to provide a mathematical model that can predict the risk of injury to the gastro- intestinal tract in a wide variety of blast environments.

Surrogate models of gut sections

Previous experiments using isolated, perfused small animal abdominal contents showed that injury is mechanically associated with the location of air bubbles in the gut sections. Further more, local pressure measurements suggested a correlation between the pressure differential across the tissue and injury. Introduction of pressure sensors into the intestinal tract is difficult and potentially injurious itself, so it is desirable to develop an understanding of the local mechanical process that can result in a less invasive approach.

Surrogate experiments have been formulated and carried out using materials with properties similar to that of the gut but formed in geometries that can be more readily analyzed. The experiments will proceed from idealized geometries and contents to configurations that closely match those found in vivo.

Measured data include pressure time histories within the bubble, in the water near the bubble, and in the water far from the bubble (chamber). The membrane was given a hemispherical geometry and filled with water and a 5 cc air bubble.

Mathematical model of bubble dynamics

A mathematical model of the dynamics of the air bubble, the membrane, and the surrounding water was developed. The model predicts the pressure and velocity in the water and the bubble given the flow geometry and the chamber pressure. The model is solved on a PC and includes run time graphic displays of the solution.

The model gives satisfactory agreement with the data when the flow pattern is assumed to be hemispherical and limited in extent to the approximate size of the enclosure holding the pressure transducers. The differential pressure is shown to arise from the inertial effects of the water, rather than the tension in the membrane.

The quality of agreement achieved would suggest that the bubble and nearby water pressure variations can be predicted without the need for an intrusive probe.

Waterjet to air blast comparisons

Experiments have been conducted to calibrate the laboratory scale water jet so that pressure loads representative of free field blast exposures can be simulated. The simplicity and repeatability of the power activated gun, however, is so great that it is likely that all experiments will use the gun.

Research Area 5: Application to Tympanic Membrane

The purpose of this research area is to provide a mathematical model that can predict the risk of injury to the tympanic membrane in a wide variety of blast environments.

Review of literature

The literature concerning the modeling of the external ear, ear canal, tympanic membrane, and the ossicular chain was collected and reviewed for the purpose of assessing the state of modeling of the mechanical processes involved in blast exposure.

Project Review Meetings

Meetings were held on the following dates and locations to review the progress of the project with the staff of Walter Reed and to set specific goals for focus of the research effort.

1. January 14, 1986 (San Diego)
2. May 12, 1986 (San Diego)
3. June 9, 1986 (Washington)
4. July 31, 1986 (Albuquerque)

Reports and Publications

1. J. H. Stuhmiller, "Experimental and Analytical Studies of blast wave effects on major organs of the body," NATO Symposium on Noise Induced Hearing Loss, Il Cicco, Italy, 23-27 Sep. 1985.

2. J. H. Stuhmiller, Y. Y. Phillips, K. T. Dodd, "Considerations in developing a mechanistically based model of blast injury to air containing organs," Third Workshop on Weapon Launch Blast Overpressure, Aberdeen, MD, 9-10 Jun. 1986.

3. J. H. Stuhmiller, J. H.-Y. Yu, E. J. Vasel, K. T. Dodd, "Use of surrogate and analytical models to understand the parameters controlling blast injury to the gastro-intestinal tract," Third Workshop on Weapon Launch Blast Overpressure, Aberdeen, MD, 9-10 Jun. 1986.

4. K. T. Dodd, M. J. Vander Vorst, and Y. Y. Phillips, "Analysis of Field test Results on the Internal Mechanical Response of Sheep to Blast Waves," Third Workshop on Weapon Launch Blast Overpressure, Aberdeen, MD, 9-10 Jun. 1986.

5. Y. C. Fung, Z. L. Tao, R. T. Yen, S. Q. Liu, H. H. Ho, "The mechanism of trauma of lung tissue subjected to compression waves," submitted to the Journal of Biomechanics.

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